Effects of Sulfur on Exhaust Emissions

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INTRODUCTION

- Most modern gasoline-fueled vehicles use catalysts to reduce HC, CO, and NOx emissions
- Sulfur is a catalyst poison. Increased sulfur levels in fuels thereby increase emissions through catalyst deactivation

INTRODUCTION

- Current MOBILE model does not have the capability to estimate sulfur's impacts on emissions. Current basis of MOBILE is results of emissions testing using Indolene, a low-sulfur fuel. An adjustment factor is used to account for emission differences between sulfur levels in Indolene and in-use fuels.

OBJECTIVES

- Identify valid data for sulfur's effect on exhaust emissions
- Develop correlations between sulfur and exhaust emissions as a function of:
  - Pollutant
  - Emitter class
  - Vehicle technology
  - Emission mode (composite, running, start)

DATA USED

- ATL-Phase I & Phase II (EPA testing programs)
  - 44 normal emitters/34 high emitters
  - All Tier 0 vehicles
  - Catalysts tested with as-received mileages
  - Sulfur levels in Phase I: 112, 371 ppm
  - Sulfur levels in Phase II: 59, 327 ppm

DATA USED

- Relevant A/O Studies
  - Phase I sulfur study
    - » 10 Tier 0 vehicles
    - » Normal emitters only
    - » Catalysts aged to ~50K miles
    - » Two levels of sulfur tested: 49, 466 ppm
  - Phase II sulfur study--Tier 0 vehicles
    - » 10 Tier 0 vehilces
    - » Normal emitters only

DATA USED

- » Catalysts aged to ~50K miles
- » 5 levels of sulfur tested: 50, 150, 250, 350, 450 ppm

– T50/T90/Sulfur study

- » 10 Tier 0 vehicles
- » 6 Tier 1 vehicles
- » Catalysts aged to ~50K miles
- » Normal emitters only
- » Two sulfur levels tested at a low T90 level and at a high T90 level: 33, 317 ppm

DATA USED

- API Extension Fuel Set
  - 10 Tier 0 vehicles
  - Normal emitters only
  - Catalysts aged to ~50K miles
  - Two high levels of sulfur tested: 450, 900 ppm

DATA USED

- CRC Sulfur/LEV Study
  - 6 LDVs models tested
  - 2 vehicles from each model type tested
  - Normal emitters only
  - Data collected with as-received catalysts (10K miles) and aged to~100K miles. Only 100K data used in this analysis
  - A total of seven fuels tested at nominal sulfur levels of 40, 100, 150, 330, 600 ppm

DATA USED

- AAMA/AIAM Sulfur/LEV Study
  - 13 LEV/ULEV LDVs
  - 8 LEV/ULEV heavier trucks
  - Only 100K mile data available
  - Normal emitters only
  - 5 nominal levels of sulfur tested: 40, 10, 150, 330, and 600 ppm

DATA USED

- API “Reversibility” Study
  - Data became available late
  - Normal emitters only
  - Two levels of sulfur tested: 40, 540 ppm
  - Only one LEV vehicle (with 100K mileage levels) used in this anlaysis

SUMMARY OF DATA

Study	# of Vehicles	Vehicle Technlgy	Range of S tested	Normal Emitters	High Emitters
A/O-Phase I Sulfur	**10**	**Tier 0**	**49-->466 (2 levels)**	**10**	**0**
A/O-Phase II Sulfur	**10**	**Tier 0**	**49-->466 (5 levels)**	**10**	**0**
A/O-T50/T90/Sul	**16**	**Tier 0, Tier 1**	**33-->318 (2 levels)**	**10 Tier 0 6 Tier 1**	**0**
EPA - ATL I	**39**	**Tier 0**	**112->371 (2 levels)**	**20**	**19**
EPA - ATL II	**39**	**Tier 0**	**59->327 (2 levels)**	**24**	**15**
CRC	**12**	**LEV**	**40->600 (5 levels)**	**12**	**0**
AAMA/AIAM	**21**	**LEV,ULEV, Trucks**	**40->600 (5 levels)**	**21**	**0**
API Extension	**1**	**LEV**	**40->540 (2 levels)**	**1**	**0**

DATA ANALYSIS

- Data not stratified by injection type
- Based on previous modeling, it is assumed that sulfur's effect on emissions has no interactions with other fuel parameters
- Two groups of vehicles analyzed: Normal and High emitters
- Correlations developed separately for composite, running and start emissions

DATA ANALYSIS

- Start and running emissions were calculated from bag data using correlations in MOBILE6 report M6.STE.002
- SAS used to generate regressions:
  - Dummy variables for vehicle effects

DATA ANALYSIS

- Repeat tests on vehicles (and for the same vehicle(s) tested in different testing programs) at a given sulfur level were averaged to represent one data point
- Two different mathematical fits were used to represent the data:
  - » Log-Log fit: ln(emis(g/m))~(R-coeff)*ln(S)
  - » Log-Linear fit: ln(emis)~(R-coeff)*S

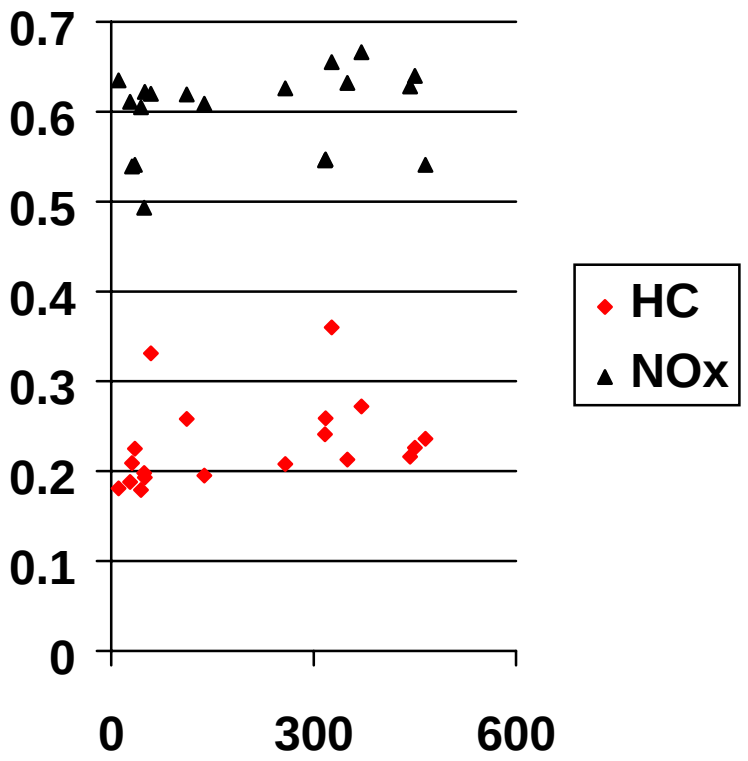
DATA ANALYSIS

- Correlations developed from data separately for:
  - Tier 0 normal emitters
  - Tier 0 high emitters
  - Tier 1 normal emitters
  - LEV/ULEV normal-emitting LDVs
  - LEV/ULEV normal-emitting heavier trucks

DATA ANALYSIS

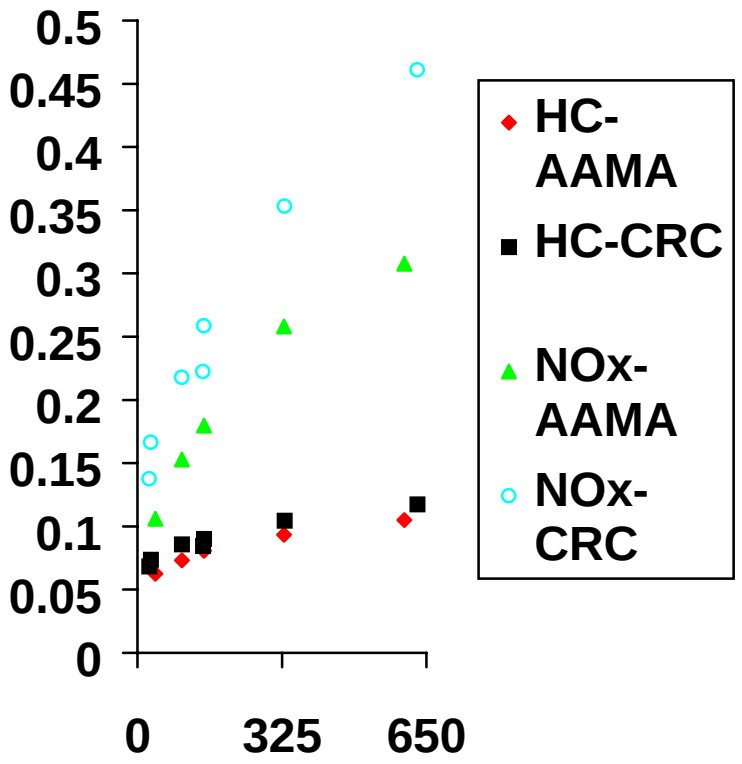
- The valid sulfur range for MOBILE6 will be limited to 30 ppm on the low end and 600 ppm on the high end

Raw g/mile data as a function of sulfur for Tier 0 normal emitters



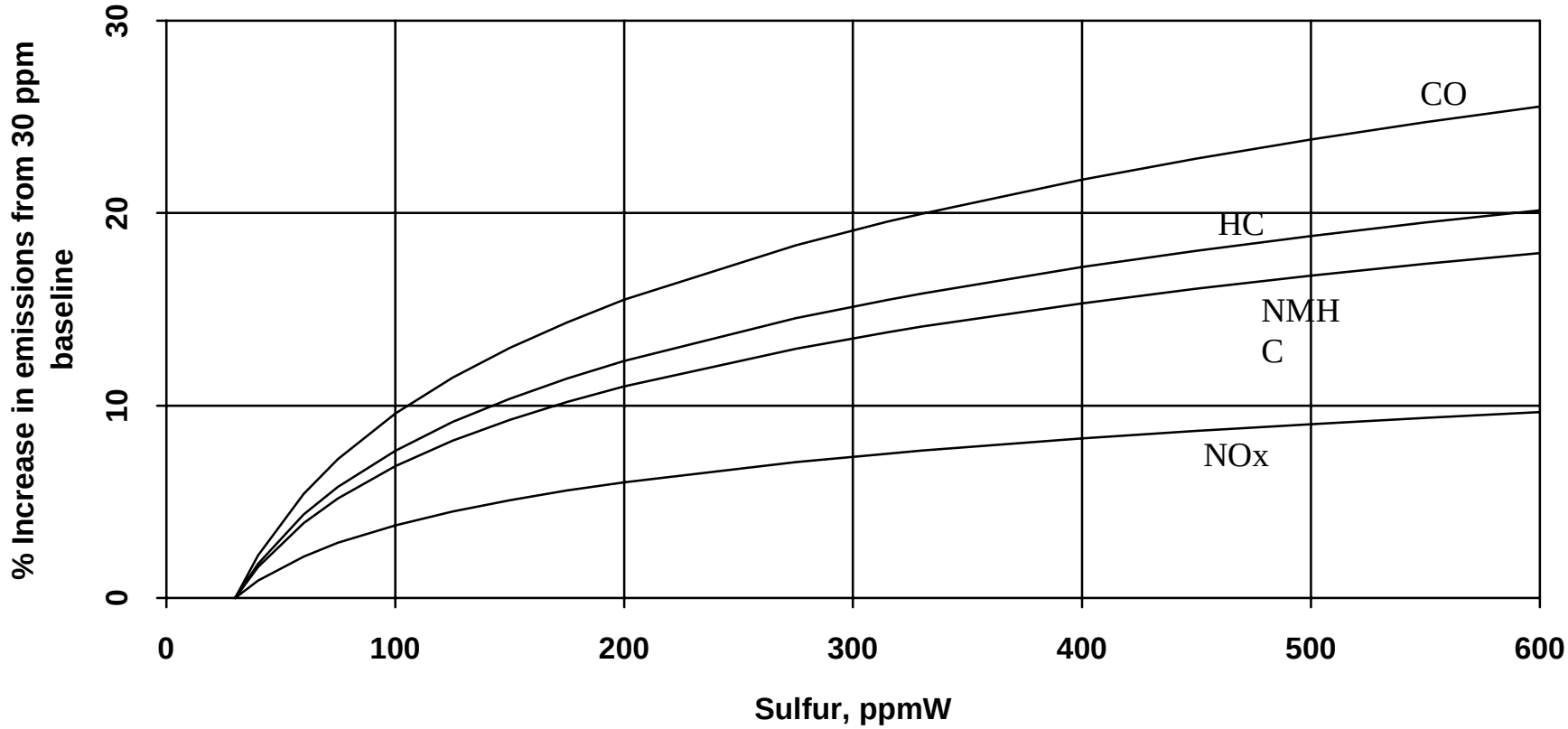
- Averaged g/mile numbers
- All Auto/Oil and EPA Studies
- Data non-linear

Avg. g/mile data as a function of sulfur for LEV/ULEV LDV Normal Emitters

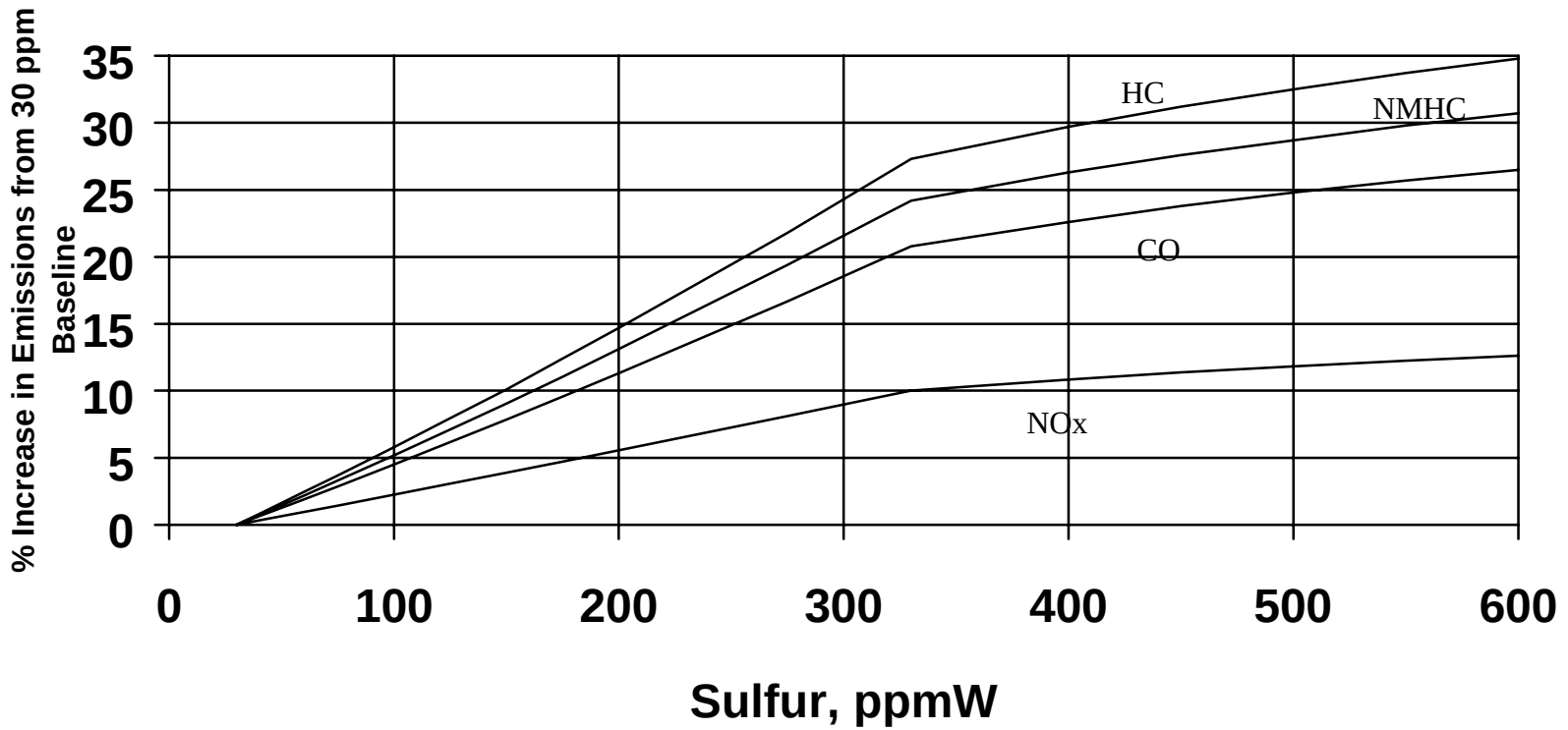


- Only 100K data included from CRC test program
- CRC data includes conventional gasoline and CA RFG data
- Non-linear effects

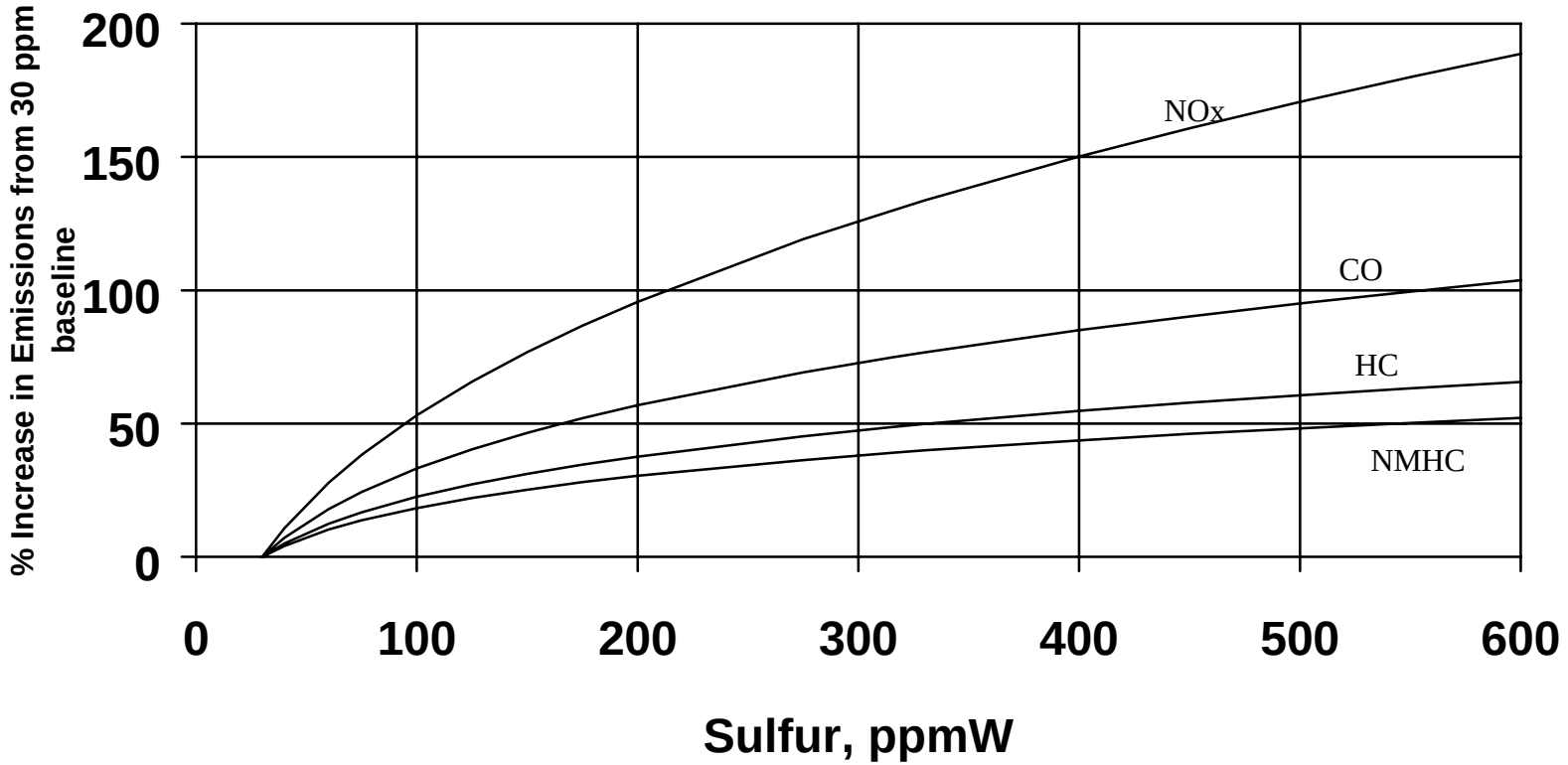
Tier 0 Normal Emitter Composite Emission Effects Based on Regression Coefficients



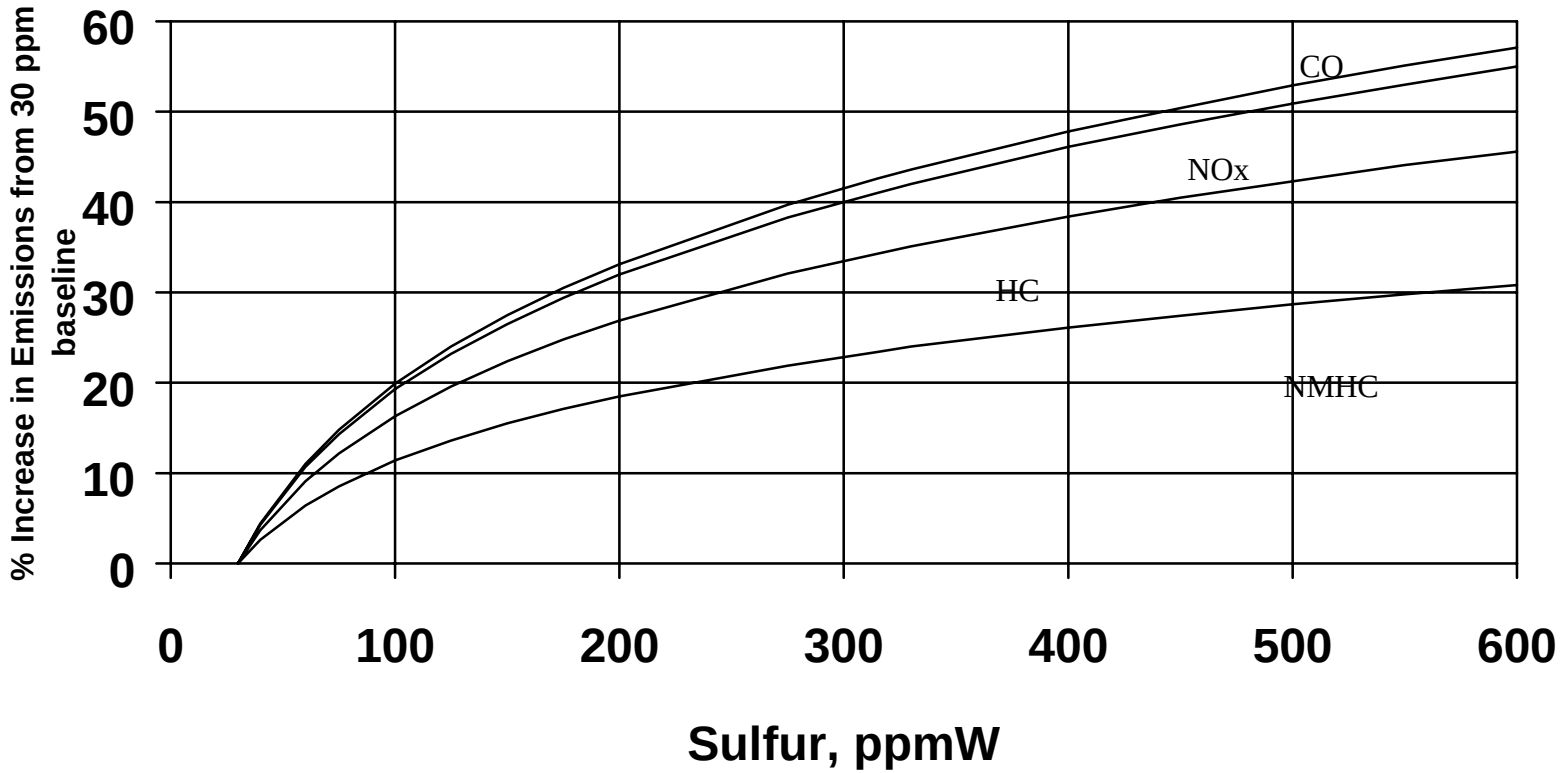
Tier 1 Normal Emitter Composite Emission Effects Based on Regression Coefficients



LEV Normal Emitter Composite Emission Effects Based on Regression Coefficients



LEV Truck Composite Emission Effects Based on Regression Coefficients



SAMPLE RESULTS:
% INCREASE IN COMPOSITE EMISSIONS WHEN SULFUR IS INCREASED FROM 30 to 330 ppmW

Pollutant	Tier 0-- Normals	Tier 1-- Normals	LEV/ULEV LDVs	LEV/ULEV Trucks	Tier 0-- Highs
HC	15.8	27.3	49.8	35.1	1.12
NMHC	14.1	24.2	39.9	24.0	1.12
CO	20.0	20.8	76.7	43.6	0.19
NOx	7.66	10.0	133.6	42.0	9.57
Avg. g/mile	HC: 0.25 CO: 2.91 Nox: 0.61	HC: 0.13 CO: 1.6 Nox: 0.3	HC: 0.085 CO: 1.34 Nox: 0.22	HC: 0.12 CO: 0.93 Nox: 0.26	HC: 2.3 CO: 31 Nox: 1.3

SAMPLE RESULTS:

% INCREASE IN RUNNING EMISSIONS WHEN SULFUR IS INCREASED FROM 30 to 330 ppmW

Pollutant	Tier 0-- Normals	Tier 1-- Normals	LEV/ULEV LDVs	LEV/ULEV Trucks	Tier 0-- Highs
HC	44.2	109.0	179.1	114.5	3.47
NMHC	43.9	138.5	228.2	88.5	2.93
CO	58.0	68.8	220.9	151.0	3.39
NOx	5.12	20.9	293.1	102.8	8.92
Avg. g/mile	HC: 0.10 CO: 1.67 Nox: 0.49	HC: 0.04 CO: 0.91 Nox: 0.25	HC: 0.03 CO: 0.82 Nox: 0.16	HC: 0.05 CO: 0.27 Nox: 0.18	HC: 1.7 CO: 27 Nox: 1.1

SAMPLE RESULTS:

% INCREASE IN START EMISSIONS WHEN SULFUR IS INCREASED FROM 30 to 330 ppmW

Pollutant	Tier 0-- Normals	Tier 1-- Normals	LEV/ULEV LDVs	LEV/ULEV Trucks	Tier 0-- Highs
HC	0.66	2.90	12.9	6.31	-6.46
NMHC	0.90	2.79	14.2	7.05	-5.32
CO	-4.21	-6.77	12.3	18.4	-14.8
NOx	12.1	27.2	30.9	10.4	7.85
Avg. g/mile	HC: 2.2 CO: 19.3 Nox: 1.7	HC: 1.5 CO: 11.4 Nox: 0.90	HC: 0.86 CO: 8.80 Nox: 0.86	HC: 1.10 CO: 11.0 Nox: 0.92	HC: 6.5 CO: 49 Nox: 0.89

SULFUR FACTOR APPLICATIONS FOR NOx

Vehicle Category	Sulfur Factor to be Used
All pre-Tier 0 Vehicles with TWCs	Tier 0
All Tier 0 Classes--Normal Emitters	Tier 0
All Tier 1 Classes--Normal Emitters	Tier 1
LDV/Truck 1 LEVs and all Tier 2	LDV LEV
LDT2/3/4 LEV	LDT2 Truck LEV
Tier 0 & Pre-Tier 0 highs	Tier 0 High
All Other highs	0.60*Normal Effect
Heavy Duty Baseline	Tier 1

SULFUR FACTOR APPLICATIONS FOR NMHC/HC/CO

Vehicle Category	Sulfur Factor to be Used
All pre-Tier 0 Vehicles with TW catalysts	Tier 0
All Tier 0 Classes--Normal Emitters	Tier 0
All Tier 1 Classes--Normal Emitters	Tier 1
LDV/Truck1 LEVs and all Tier 2	LDV LEV
LDT2/3/4 LEVs	LDT2 Truck LEV
All High Emitters	Tier 0 High Emitter
Heavy Duty Baseline	Tier 1

CONCLUSIONS

- Low emission vehicle technology (both LEV and ULEV) is much more sensitive to fuel sulfur than earlier generation technology.
- More data needed on high emitter effects
- Reversibility issues not addressed in this analysis